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Financial contracts as coordination device

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Abstract

We study the use of financial contracts as bid-coordinating device in multi-unit uniform price auctions. Coordination is required whenever firms face a volunteer's dilemma in pricing strategies: one firm (the "volunteer") is needed to increase the market clearing price. Volunteering, however, is costly, as inframarginal suppliers sell their entire capacity whereas the volunteer only sells residual demand. We identify conditions under which signing financial contracts solves this dilemma. We test our framework exploiting data on contract positions by large producers in the New York power market. Using a Monte Carlo simulation, we show that the contracting strategy is payoff dominant and provide estimates of the benefits of such strategy.

KEYWORDS

auctions, coordination, electricity, forward markets, volunteer's dilemma

JEL CLASSIFICATION

D21; D44; L41; L94

1 | INTRODUCTION

A variety of goods and services are traded in multi-unit auctions. Classic examples include auctions for government bonds (Hortaçsu, Kastl, & Zhang, 2018), spectrum rights (Cramton & Ockenfels, 2017), electricity (Fabra, von der Fehr, & Harbord, 2006), emission allowances (Lopomo, Marx, McAdams, & Murray, 2011), or gas pipeline capacity (Newbery, 2002). The majority of multi-unit auctions clear at a uniform price, which facilitates market entry (Ausubel, Cramton, Pycia, Rostek, & Weretka, 2014). Depending on the market architecture, bidders may also take financial positions on forward markets before participating in the auction.

The theoretical literature on strategic forward trading shows that forward contracts affect spot market prices, either by enhancing or softening spot market competition (e.g., Allaz & Vila, 1993; Mahenc & Salanié, 2004). An example that seems to contradict the extant findings, however, was observed in the New York power market, which operates as a multi-unit uniform price auction. Whereas two major producers signed forward contracts in 2006, the market price stayed equal to the regulatory price cap before and after the contract start date. Both the U.S. Federal Energy Regulatory Commission (FERC) and the Department of Justice (DOJ) investigated whether the contractual agreements constituted market manipulation. Their findings differed significantly. FERC (2008) argued against market manipulation and concluded that the contracts were instruments to hedge price risk. DOJ (2010), following Cramton (2007), found that the contracts helped firms to avoid competitive bidding strategies.

Drawing from this case, we present a new theoretical framework to examine how forward contracts allow firms to coordinate on one of multiple equilibria in the spot market. Previous findings on the strategic use of forward contracts illustrate how firms use contracts to gain additional market share, leading to lower spot prices (Allaz & Vila, 1993) or how firms use contracts to increase spot prices (Mahenc & Salanié, 2004). We thus offer a new rationale for signing forward contracts, which is to avoid miscoordination in pricing strategies. We also contribute with an empirical investigation of this rationale. So far, the extent empirical literature on strategic forward contracts has shown price-reducing effects of forward contracts (e.g., Wolak, 2003) and strategic price premia on forward markets (Ito & Reguant, 2016). To our knowledge, empirical findings on price coordination through forward contracts have not been documented so far. We apply and test our model using rarely observed data on firms' financial positions from the case investigated by FERC and DOJ. Simulating market outcomes with and without contracts, we show that forward positions rule out competing (off-)equilibrium outcomes and allow firms to coordinate on their pricing strategies.

For our theoretical analysis, we model a standard multi-unit uniform price auction. The literature on multi-unit auctions considers continuous bid functions (e.g., Hortacsu & Puller, 2008; Klemperer & Meyer, 1989; Wilson, 1979) and discrete bids (e.g., Fabra et al., 2006; Kastl, 2006, 2012). Moreover, Kastl (2012) finds that as the number of steps increases, equilibrium conditions for discrete and continuous supply functions converge. In line with previous auction literature applied to electricity markets (e.g., Fabra et al., 2006; Reguant, 2014; Schwenen, 2015), we however focus on discrete bids as they well resemble the market environment that we study. Specifically, we model two large firms and a competitive fringe. Before auction clearing, the two large firms can sign forward contracts with a financial intermediary. If neither firm's capacity is sufficient to satisfy full demand, all pricing equilibria are characterized by one pivotal firm that clears the auction. This price-setting firm can charge a supra-competitive price due to its market power vis-á-vis residual demand. Yet, the firm compromises on selling parts of its capacity, similarly to how a standard monopoly firm would. Due to the institutional setup in the New York power market, we model a game of complete information.[1]

As Le Coq, Orzen, and Schwenen (2017) point out, firms in such a game face a coordination problem akin to the volunteer's dilemma (Diekmann, 1985; Goeree, Holt, & Smith, 2017): one firm (the "volunteer") is needed to increase the market clearing price.[2] Volunteering, however, is costly, as inframarginal suppliers sell their entire capacity whereas the volunteer only supplies residual demand. Our model illustrates conditions under which signing financial contracts solves this dilemma. More precisely, we show that signing opposite forward contracts increases both firms' profits when firms face the volunteer's dilemma. The contracts work as follows. The volunteering firm holds a long position, while the nonvolunteering firm holds a corresponding short position. By holding a long position, the volunteer obtains the high clearing price not only for its spot sales, but also for its financially contracted quantity. The other ("free-riding") firm, while losing money via the contract, benefits as it sells full capacity with certainty, knowing that its rival volunteers.

We test our theoretical predictions by analyzing pricing strategies and contract choices in the New York power market. Focusing on this market offers several advantages. First, the fundamentals of this market, for example, on marginal costs, are in line with the characteristics of our model. Furthermore, the market was highly concentrated during our period of observation, which corresponds to our model with dominant and fringe firms. Moreover, our setting allows for exploiting detailed data on demand curves and firm capacities. Finally, given that the contracts at stake were publicly investigated, we can make use of detailed information on underlying contract positions.

For our empirical analysis, we conduct a Monte Carlo simulation of market outcomes with and without observed contracts. We first show that, without contracts, the two largest firms would face a volunteer's dilemma: There exist two types of equilibria, in each of which one firm volunteers. Second, in line with our predictions, we find that the contract positions ruled out one of the two types of competing equilibria of the volunteering game. Third, we show that firms' contracting strategies were weakly payoff dominant, even at constant clearing prices before and after the contract start date. Our empirical investigation further illustrates that profits obtained via the forward market were just sufficient to achieve commitment and to reward the price-setting firm for its volunteering role.

Our paper is closely related to the literature on strategic interaction in forward and spot markets as pioneered by Allaz and Vila (1993). Starting from an oligopoly equilibrium on the spot market, they prove a competition-enhancing effect of forward markets. However, whether contracting triggers aggressive pricing behavior depends crucially on the institutional and structural market features, for example, on whether market participants interact repeatedly

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[1]Demand, firm capacities, and also bids submitted to the auction are published ex-post and hence firms can infer and learn about their competitors' forward and spot sales. We also assume that contract positions of the dominant firms are common knowledge. This is in line with our empirical case, where the financial intermediary publicly searched for counterparties for the contract and later was accused of coordinating financial flows, having to pay 4.8 USD million in disgorgement (DOJ, 2012).

[2]Alternatively, the volunteer's dilemma can be interpreted as an N-person battle of the sexes.

(Liski & Montero, 2006), on the distribution of contracts among firms (de Frutos & Fabra, 2012), on the availability of option contracts (Holmberg & Willems, 2015), as well as on arbitrage opportunities (Ito & Reguant, 2016).

The paper closest to ours is Mahenc and Salanié (2004). They show that when products are differentiated and prices are strategic complements, producers can buy their production forward to soften spot market competition. We study a setup where firms sell a homogeneous product in multi-unit uniform price auctions. In this context, "buying forward strategies" payoff even when firms do not alter market prices. In our analysis, financial contracts establish coordination on bidding strategies amid multiple equilibria on the spot market and effectively redistribute rents. This mechanism is similar to the one outlined in the industrial organization literature on side payments to enforce collusion (e.g., Harrington & Skrzypacz, 2007). In our case, financial contracts make side payments credible by conditioning payments on the market outcome.

Our paper is also related to the empirical literature on strategic firms signing forward contracts (e.g., Hortacsu & Puller, 2008; van Eijkel, Kuper, & Moraga-González, 2016; Wolak, 2003) or investing in new capacities (Grimm & Zoettl, 2013), before competing on the spot market. Moreover, Schwenen (2015) studies spot market bidding behavior in the New York power market from 2003 to 2008. He empirically investigates the optimality of bidding strategies for all participating firms. We look at a subset of his observation period, and add to this paper by studying how contracting changes the incentives to (not) volunteer for the two largest firms.

Finally, this paper also relates to the game theory literature on coordination games, as in our case firms have to coordinate on a volunteer, and miscoordination is costly. In the laboratory, Goeree et al. (2017) show that miscoordination (e.g., the no-volunteer outcome) increases with the number of players. Our model shows how contract payments contingent on the outcome of the game solve the volunteer's dilemma.[3]

The next section characterizes the auction model and the resulting volunteer's dilemma. Section 3 characterizes conditions under which forward contracts solve this dilemma. Section 4 tests our theoretical predictions using a Monte Carlo simulation. Section 5 discusses model extensions to a broader set of market environments. Section 6 concludes.

2 | THE MARKET ENVIRONMENT

We consider a standard multi-unit uniform price procurement auction framework (e.g., Fabra et al., 2006) and derive necessary conditions for a volunteer's dilemma in bidding strategies.

Two large and strategic firms $i, j = 1, 2$ with $i \neq j$, and a competitive fringe participate in a multi-unit uniform price auction.[4] Before bidding, the auctioneer publicly announces a demand function. In line with our empirical application we assume linear demand of

$$D(p) = a - dp, \tag{1}$$

with market price p and constant parameters a and d.

All firms have zero marginal costs. Each large firm i offers a price-quantity pair (b_i, k_i), where k_i is the exogenous maximum quantity that firm i is willing to sell at or above an equilibrium auction price of b_i.[5] The fringe acts as price-taker and therefore always submits its full capacity k_f at marginal costs, that is, at prices of zero.

The clearing price $p*$ equates demand and supply. The auction clears with uniform pricing so that all bids below the clearing price win and receive the latter. To limit procurement costs, the auctioneer imposes a price cap $\bar{p}$. Bids are perfectly divisible. We further assume that both dominant firms are pivotal in clearing the auction at any positive price equal to or below the price cap.

Assumption 1 (Pivotal firms and no rationing). For each large firm $i = 1, 2$ with $i \neq j$, $D(\bar{p}) - k_f - k_j > 0$ and $D(b_i|b_i = p*) \leq k_f + k_i + k_j$ holds, where $b_i = p* \in [0, \bar{p}]$ is the optimal bid of the price-setting firm i.

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[3]Boom (2008) uses equilibrium selection arguments to rule out multiple equilibria in multi-unit auctions. Applying risk-dominance criteria, it can be shown that larger firms set the clearing price. In a supply function equilibrium model, Hortaçsu, Luco, Puller, and Zhu (2019) reduce the number of equilibria using a Cognitive Hierarchy model.

[4]The fringe supply is not needed for our main theoretical arguments. We add fringe firms to align the model to our empirical application.

[5]The maximum quantity that firm i is willing to sell corresponds to its exogenously given installed capacity k_i. The choice of submitted capacity, potentially smaller than k_i, is not relevant for our main results. Also note that the assumption of discrete one-step bid functions simplifies the exposition without changing the results. As shown by Fabra et al. (2006), the equilibrium clearing price is independent of the number of bid steps. Figure B4 graphs the auction outcome for one representative auction, May 2006, and shows that the assumption of discrete bids captures firm behavior in the market that we study reasonably well.

Firm i's profits can be written as

$$\pi_i = q_i(b_i, b_j, k_f)p^*, \tag{2}$$

where firm i's quantity sold in the auction, $q_i(b_i, b_j, k_f)$, is defined as

$$q_i(b_i, b_j, k_f) = \begin{cases} k_i & \text{if} \quad b_i < b_j = p^* \\ \dfrac{k_i}{k_i + k_j}(D(p^*) - k_f) & \text{if} \quad b_i = b_j = p^* \\ D(p^*) - k_f - k_j & \text{if} \quad b_i = p^* > b_j. \end{cases} \tag{3}$$

In case of bid ties the auctioneer rations supply at the margin pro rata.[6]

2.1 │ Volunteer's dilemma

Given Assumption 1 and the allocation rule in (3), all firms but the price-setting one sell their entire submitted capacity. The price-setting bidder, in contrast, satisfies residual demand. Each firm hence prefers a market outcome in which its rival firm acts as price-setter. Conversely, accepting the role of price-setter is a best response if rivals choose against playing this role.

Bidders consequently face a volunteer's dilemma (Diekmann, 1985), where one price-setting bidder (the volunteer) is needed for all rivals to sell their submitted capacity at a favorably high price. However, volunteering is costly as bidders who price high and increase the clearing price on behalf of the market sell less as compared with undercutting their rival.

Next, we characterize the volunteer's dilemma more formally. When firm i volunteers to submit the clearing bid, so $b_i > b_j$, it optimizes against its residual demand and finds the optimal clearing bid

$$b_i^V = \min\{\arg\max_{b_i} q_i(b_i, b_j, k_f)b_i, \bar{p}\}, \tag{4}$$

where the superscript V denotes the optimal bid of a firm that volunteers to clear the market. Firm i volunteers if offering b_i^V is a more profitable strategy than undercutting its rival bid b_j. Formally, this holds if $\pi_i(b_i^V) = b_i^V q_i(b_i^V, \cdot) > \pi_i(b_i < b_j) = b_j k_i$. This inequality is fulfilled if firm j, in turn, chooses a bid b_j sufficiently low such that it is never optimal for firm i to undercut. This is the case if the free-riding firm j submits any bid

$$b_j^F \in [0, \bar{b}_j) \quad \text{with} \quad \bar{b}_j = \frac{b_i^V q_i(b_i^V, \cdot)}{k_i}, \tag{5}$$

where the superscript F denotes bids by any firm $i, j = 1, 2$ with $i \neq j$ that free-rides, becoming the inframarginal bidder and selling at full capacity.

Depending on whether or not the price cap is binding, the volunteering firms' equilibrium profits become

$$\pi_i(b_i^V) = \begin{cases} \dfrac{(a - k_f - k_j)^2}{4d} & \text{if} \quad b_i^V < \bar{p}, \\ \bar{p}(D(\bar{p}) - k_f - k_j) & \text{if} \quad b_i^V = \bar{p}. \end{cases} \tag{6}$$

The first part of the equation, when the price cap is not binding, corresponds to the profits associated with bid $b_i^V = \frac{a - k_f - k_j}{2d} < \bar{p}$ as defined in Equation (4). The second part of the equation, when the price cap is binding, corresponds to the profits from selling residual demand of q_i as defined in Equation (3) at a price equal to the cap.

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[6]Holmberg (2017) shows how alternative rationing rules impact auction outcomes.

Due to the uniform price auction, the free-riding firm i sells all of its submitted quantity at the high price set by its rival and receives profits

$$\pi_i\left(b_i^F\right) = \begin{cases} \dfrac{a - k_f - k_i}{2d}k_i & \text{if} \quad b_j^V < \bar{p}, \\ \bar{p}k_i & \text{if} \quad b_j^V = \bar{p}. \end{cases} \tag{7}$$

Given that volunteering is the best response to a free-riding rival, there are multiple equilibria that differ in the identity of the volunteering firm as well as the low bid offered by the free-riding firm. The volunteer's dilemma arises because each firm always prefers that the other one volunteers and sets the clearing price.

The volunteer's dilemma applies to a subset of existing equilibria described by Fabra et al. (2006) and de Frutos and Fabra (2012). In particular, for the dilemma to be relevant, the dominant firms must be sufficiently symmetric in capacities, as specified in Lemma 1.

Lemma 1 (Sufficient symmetry). *A volunteer's dilemma exists if the two pivotal firms are sufficiently symmetric such that $k_i \le k_j < \hat{k}_j(k_i)$ where $\hat{k}_j(k_i)$ satisfies $\pi_j(b_j < b_i^V(\hat{k}_j)) > \pi_j(b_j^V(k_i) > b_i)$ with $i = 1, 2$ and $i \neq j$.*

Intuitively, Lemma 1 states that the relative capacities must be such that each firm prefers to be the inframarginal supplier. Hence $\hat{k}_j(k_i)$ characterizes the maximum capacity of the largest firm j for which the volunteer's dilemma still exists.

The functional form of $\hat{k}_j(k_i)$ follows from comparing firm j's profits from being inframarginal of $\pi_j(b_j < b_i^V(k_j))$ with profits from volunteering of $\pi_j(b_j^V(k_i) > b_i)$. When the price cap is nonbinding, the condition in Lemma 1 becomes $\frac{a - k_f - k_j}{2d}k_j > \frac{(a - k_f - k_i)^2}{4d}$. Equating and solving for k_j yields the sufficient symmetry condition in Lemma 1. When the largest firm's capacity is above this threshold, the remaining demand and hence the clearing price set by its rival are so small that the larger firm prefers to clear the auction itself. As a result, the volunteer's dilemma vanishes. We derive $\hat{k}_j(k_i)$ in detail in Appendix A.1.

Note that $\hat{k}_j(k_i)$ includes the case of binding price caps for both dominant firms. In this case, firm j yields profits $\bar{p}k_j$ when free-riding and $\bar{p}(D(\bar{p}) - k_f - k_i)$ when volunteering. When price caps are binding, the only case where free-riding profits would not be larger is the case where $k_j < D(\bar{p}) - k_f - k_i$, which is ruled out by Assumption 1.

Corollary 1. *For any equilibrium $(b_i^V = \bar{p}, b_j^F < \bar{b}_j) \quad \forall i = 1, 2$ and $i \neq j$, the volunteer's dilemma exists.*

Hence if the price cap is the optimal bid independent of the identity of the price-setting firm, the volunteer's dilemma must exist. Corollary 1 follows directly from Assumption 1, which rules out rationing demand. Demand rationing constitutes the only case where both firms could submit a bid equal to the cap without compromising on sales and hence without facing the volunteer's dilemma.

3 | FINANCIAL CONTRACTS AS COORDINATION DEVICE

In this section we study how firms' financial positions impact the volunteer's dilemma. Specifically, we show that by signing forward contracts, firms are able to coordinate on the identity of the volunteering firm and avoid miscoordination at the auction stage. Contracts are financial, hence they specify payments and no physical delivery.

3.1 | Optimal bidding with contracts

We study a standard forward contract with a forward price $p^s \in [0, \bar{p}]$ and firm-specific contract quantity s_i. Contract payments are given by $(p^* - p^s)s_i$. We assume that before interacting on the spot market, each large firm learns about its rival's position. With contracting, firm i's profits can be written as

$$\pi_i = q_i(b_i, b_j, k_f)p^* + (p^* - p^s)s_i. \tag{8}$$

Following conventional notation, the quantity contracted forward, s_i, is positive (negative) if firm i is a net buyer (seller) on the contract market. That is, for any positive s_i, firm i receives payments whenever the clearing price is above the strike price. Payments instead reverse if the clearing price is below the strike price. If s_i is negative, payments flow in the opposite direction. Note that the case with negative s_i where firms are selling ahead is also studied in Allaz and Vila (1993), Wolak (2003), Hortacsu and Puller (2008), and Green and Le Coq (2010), while Mahenc and Salanié (2004) analyze the case where firms buy forward in equilibrium.

Given its contract position, the optimal clearing bid for a volunteering firm i is given by

$$b_i^V = \min\{\arg \max_{b_i} q_i(b_i, b_j, k_f)b_i + (b_i - p^s)s_i, \bar{p}\}. \tag{9}$$

When the price cap is nonbinding, Equation (9) yields an optimal clearing bid of $\frac{a - k_f - k_j + s_i}{2d}$, so the clearing bid b_i^V increases in s_i. Given the uniform pricing format, free-riding firms' profits thus also increase in s_i. With a binding price cap however, positive forward positions of the price-setting firm do not increase market prices or producer rent on the spot market.

In the following subsection, we focus on the case that we study in our empirical analysis, that is, the case where the price cap is binding. Specifically, we show that by signing two offsetting forward contracts, firms can swap profits to establish coordination at the auction stage. We discuss nonbinding price caps in Section 5 and present a characterization of equilibrium bidding for this case in Appendix A.4.

3.2 | Coordination with contracts

In this section, we first state a Lemma on our main result, that is, a firm can credibly commit to free-ride by holding a critically large short position. We then introduce a Corollary to narrow down this commitment for the case of miscoordination profits of zero.

To ensure coordination, contracts must rule out one of the two pure-strategy equilibria (b_i^V, b_j^F) with $i = 1, 2$ and $i \neq j$. Without loss of generality, we consider the case where firm j volunteers given its contract position. Contracts, therefore, must rule out the equilibrium (b_i^V, b_j^F). For this to be the case, the contract must ensure that firm i's best reply to firm j bidding low is to also bid low. Put differently, the contract renders free-riding bids of firm j unprofitable. If this condition is fulfilled, firm i can use its contract position to credibly commit to free-ride. Formally, firm i must sign a contract such that

$$\pi_i\left(b_i^V, b_j^F\right) + (\bar{p} - p^s)s_i < \pi_i\left(b_i^F, b_j^F\right) + (p^* - p^s)s_i. \tag{10}$$

The left-hand side of this inequality includes firm i's profits for $b_i^V = \bar{p}$ plus contract payments. The right-hand side represents firm i's profits in case both firms submit low free-riding bids, again plus contract payments. In the latter case, the market price p^* is determined by $\max\{b_i^F, b_j^F\}$. Rearranging the inequality yields

$$s_i < -\frac{\pi_i\left(b_i^V, b_j^F\right) - \pi_i\left(b_i^F, b_j^F\right)}{\bar{p} - p^*}. \tag{11}$$

Equation (11) states that for all contract positions of firm i below s_i, the contract commits firm i to not volunteer, even if firm j prices aggressively and submits b_j^F. Note that for b_i^F and b_j^F multiple equilibria exist (see Equation 5). Thus different equilibrium outcomes for $\pi_i(b_i^F, b_j^F)$ can occur and thus define different critical contract positions s_i. However, it must hold that $s_i < 0$ because by definition $\bar{p} - p^* > 0$, and for the volunteer's dilemma to exist we have $\pi_i(b_i^V, b_j^F) - \pi_i(b_i^F, b_j^F) > 0$. We summarize this finding in the following Lemma.

Lemma 2 (Critical contract position). *Firm* i *commits to free-ride by holding a short position. Specifically, firm i's critical contract position must satisfy* $s_i < -\frac{\pi_i(b_i^V, b_j^F) - \pi_i(b_i^F, b_j^F)}{\bar{p} - p^*} < 0.$

The critical contract position s_i in Lemma 2 is independent of the forward price. This is because the contract payments $-p^s s_i$ occur in any case, that is, on both sides of Equation (10). However, the contract impacts profits at the auction stage via the difference between the forward price and the clearing price. Given firm i's contract position, firm j has an incentive to volunteer, and so the clearing price will be equal to the price cap. In turn, together with $s_i < 0$ this implies total contract payments for firm i of $(\bar{p} - p^s)s_i < 0$. Put differently, firm i pays $(\bar{p} - p^s)s_i$ for incentivizing firm j to volunteer. Consequently, the commitment is costly to firm i.

Equation (11) also shows that for a larger difference in volunteering and free-riding profit, $\pi_i(b_i^V, b_j^F) - \pi_i(b_i^F, b_j^F)$, firm i also has to increase its short position (further reduce s_i) to achieve commitment. The short position that yields commitment in all cases, that is for all outcomes for $\pi_i(b_i^F, b_j^F)$, is hence a contract that assumes $b_i^F = b_j^F = 0$ and, consequently, $\pi_i(b_i^F, b_j^F) = 0$. In this case, firm i's condition for credible commitment yields

$$\pi_i\left(b_i^V, b_j^F\right) + (\bar{p} - p^s)s_i < -p^s s_i. \tag{12}$$

Using $\pi_i(b_i^V, b_j^F) = \bar{p}(D(\bar{p}) - k_f - k_j)$, the critical contract position can be rearranged to

$$s_i < -D(\bar{p}) + k_f + k_j. \tag{13}$$

Since by assumption dominant firms are pivotal, we again have $s_i < -D(\bar{p}) + k_f + k_j < 0$.[7] We summarize this finding, that we test in our empirical application, by the following corollary.

Corollary 2 (Sufficient contract position). *Any short position of $s_i^* < -D(\bar{p}) + k_f + k_j < 0$ is a sufficient contract position for firm i to commit to not volunteer. That is, this contract position suffices to implement commitment for all outcomes of $\pi_i(b_i^F, b_j^F)$.*

Lastly, note that the volunteering firm j can sign an exactly offsetting contract $s_j = -s_i$. For any $s_j \geq 0$, firm j maximizes profit by bidding the price cap, because $\frac{\partial b_j^V}{\partial s_j} > 0$ (see Equation 9). As a result, when firm j signs an offsetting contract with $s_j = -s_i$, the two contracts together redistribute rents of $(\bar{p} - p^s)s_j$ from the free-riding firm i to the price-setting firm j.

Whether two offsetting contracts are beneficial to both dominant firms depends on counterfactual profits without the contract. In the empirical section, we use mixed-strategy profits as a counterfactual and illustrate that contracts, as studied above, not only implement credible commitment but also increase payoffs for both contract parties.

4 | APPLICATION

In this section, we employ a Monte Carlo simulation to test our model. We exploit data from the New York City power market as well as data from financial contracts signed by two dominant firms participating in this market. All data are available on the website of the New York independent electricity system operator (NYISO).[8]

4.1 | Market institutions and data

Our application makes use of data from the NYC procurement auctions for power-generating capacity. For each calendar month, the NYISO procures the generating capacity needed to cover maximum electricity demand. The regulatory rationale for doing so is to secure sufficient generation capacity at all times to avoid black-outs and rationing. To this end, the NYISO conducts a procurement auction and publicly announces a demand curve for available capacity. The demand curves are announced seasonally. The NYISO announces one winter demand curve that applies in six monthly auctions during a predefined "winter period" between November and April, and one summer demand curve

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[7]Appendix A.2 provides another argument why the critical contract position must be the largest for $\pi_i(b_i^F, b_j^F) = 0$.

[8]The data that support the findings of this study are available at https://www.nyiso.com.

for six monthly auctions in the "summer period" from May to October. Winning bidders receive a monthly payment for holding capacity available during the respective month. As generating units commit to be available one month ahead, opportunity costs for generation are limited, and marginal costs are near zero (Cramton & Stoft, 2005). We therefore disregard costs in our simulation.

Capacity can be sold in sequential markets. The NYISO conducts forward procurement auctions and deducts all previously sold capacity from the demand in the final spot auction. As we lack sufficient data on the allocation of firm-specific capacity among the sequential markets, we abstract from sequentiality in our simulation and map the total firm capacities against total demand during the summer and winter periods.

The two firms involved in the contract were two dominant firms in the market, Astoria and Keyspan. The contract payments started with procurement auctions for the summer 2006 season and were to last until 2009. The contract at stake specified payments for 1,800 MW. Based on this quantity, payments were determined by calculating the difference between the auction clearing price and a predefined strike price. Astoria, the inframarginal firm in the market, took a short position and is the low-bidding firm i in our theoretical framework. Keyspan took the offsetting long position and is the volunteering firm j. The strike price differed marginally for either firm to guarantee a margin for the financial intermediary that acted as a counterparty for the two dominant firms.[9]

In addition to information on the contract, the data comprise demand curve parameters and firm-level capacities for the six major firms operating in the NYC power market. Capacities are scraped from the annual NYISO reports that list all installed generation capacity for the state of New York. Capacities are reported in terms of available capacity ("capability").[10] Available capacity determines the amount of capacity that firms can offer to the procurement auction. Due to seasonal outages or maintenance patterns, available capacity is, like the demand curves, determined by season.

For our model simulations, we use data from 2006, the first contracting year. Table 1 presents the data on demand as well as data on the capacities of Astoria, Keyspan, and the fringe firms operating in the NYC capacity market, both before and for the first year of the contract period. As apparent, the firm's capacities and the demand vary slightly from year to year and across seasons. The four fringe firms' capacities are aggregated. Astoria increased its capacity by around 600 MW in 2006, as shown by the differences from summer and winter 2005–2006, respectively.[11] The last column of Table 1 depicts demand at the price cap, as announced by the NYISO.

Whereas procurement auctions clear monthly vis-à-vis seasonally defined demand curves, the granularity of our simulation is bound to information on the half-yearly capacities in Table 1. This also forces us to apply a Monte Carlo simulation rather than pursuing regression methods.

In contrast to the model with one common price cap, the NYISO capacity market features firm-specific bid caps that differ marginally across firms. For Astoria, the bid caps are at $12.34 and $5.67 for summer and winter 2006, respectively. For Keyspan, the bid caps are at $12.71 and $5.84 for summer and winter 2006, respectively.

For our simulations, we set the predefined forward price as specified in the contract, so at $7.57 for Keyspan and $7.07 for Astoria. The difference is the margin for the financial intermediary. To illustrate the difference to observed clearing prices, Figure B1 displays observed monthly market prices (equal to Keyspan's bid cap) and the forward prices for three seasons before and after the contract start date. Note that the price cap is below the forward price during winter months. This implies that payments in winter must flow reverse, that is, from the pivotal to the inframarginal firm. We, therefore, analyze swapped payments over the course of one full year, over both summer and winter markets combined. We thus capture the net effect of payments from the low-bidding to the volunteering firm across seasons and for an entire year.

4.2 | Empirical strategy

Our simulation strategy proceeds in three steps. First, we test whether there indeed exists a volunteer's dilemma in the absence of the contract. To do so, we test whether firms are pivotal and whether the price cap is binding for both firms (in line with Corollary 1). Second, we test whether the contract provides credible commitment for Astoria to not

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[9]FERC (2008) and DOJ (2010) provide detailed information on the contract parties and parameters.

[10]Available capacity is an estimate using NYISO's algorithm based on historical plant availability.

[11]DOJ (2010) argues that this investment, as part of a total of 1,000 MW newly entered capacity, has motivated the contract, because the investments further decreased the incentives to volunteer in this market. Indeed, next to Astoria's investment there has been a large capacity addition of about 450 MW by the New York Power Authority. The NYISO lists these 450 MW already for 2005 and hence this investment is included in the 2005 data in Table 1.

TABLE 1 Firm capacities and demand one year before and during first year of contract

	Capacities (MW)			Demand (MW)
Season	**Astoria [k_i]**	**Keyspan [k_j]**	**Fringe [k_f]**	**[$D(\bar{p})$]**
Summer 2005	2,121	2,382	5,022	8,859
Winter 2005	2,400	2,536	5,525	9,440
Summer 2006	2,679	2,305	5,034	9,093
Winter 2006	3,073	2,463	5,486	9,824

volunteer. We hence test whether the observed contract quantity of 1,800 MW is at least equal to the contract quantity that is required for successful coordination (in line with Corollary 2, we test whether the contract always triggers commitment, i.e., against $\pi_i(b_i^F, b_j^F) = 0$). Third, we test whether each firm has an incentive to sign the contract. We investigate whether contracting and thus avoiding coordination failure yields higher profits for both firms as compared to hypothesized counterfactual profit.

4.2.1 | Profits without the contract

To capture counterfactual profits without contract positions, we derive expected profits against which firms decide on their contracting strategy. As in Goeree et al. (2017), we consider a mixed-strategy equilibrium in which each firm i volunteers with probability ρ_i. Firm j's mixed strategy is characterized by making firm i indifferent between volunteering and free-riding. Formally,

$$\rho_j \pi_i\left(b_i^V, b_j^V\right) + (1 - \rho_j)\pi_i\left(b_i^V, b_j^F\right) = \rho_j \pi_i\left(b_i^F, b_j^V\right) + (1 - \rho_j)\pi_i\left(b_i^F, b_j^F\right), \tag{14}$$

where ρ_j is the likelihood that firm j volunteers. The left-hand side represents expected profits when firm i is volunteering, whereas the right-hand side shows expected profits when firm i is free-riding. To compute mixed-strategy profits with the same support, we calculate mixed strategies using Astoria's price cap. Also Table 1 reports demand at Astoria's price cap.[12]

The computation of expected profits then immediately follows. In particular, under the volunteer's dilemma, firm i's expected profits are given by mixed-strategy profits

$$\pi_i^{\text{mixed}} = \frac{\pi_i\left(b_i^V, b_j^V\right)\pi_i\left(b_i^F, b_j^F\right) - \pi_i\left(b_i^V, b_j^F\right)\pi_i\left(b_i^F, b_j^V\right)}{\pi_i\left(b_i^F, b_j^F\right) - \pi_i\left(b_i^V, b_j^F\right) - \pi_i\left(b_i^F, b_j^V\right) + \pi_i\left(b_i^V, b_j^V\right)}. \tag{15}$$

We derive mixed strategies and expected profits in detail in Appendix A.3. As the critical contract position, mixed-strategy profits depend on the specification of $\pi_i(b_i^F, b_j^F)$. We show in the Appendix that for $\pi_i(b_i^F, b_j^F) = 0$ mixed-strategy profits can be written as $\rho_j \pi_i(b_i^F, b_j^V)$. Further, mixed-strategy profits with $\pi_i(b_i^F, b_j^F) = 0$ constitute an upper bound on counterfactual profits without the contract $\left(\frac{\partial \pi_i^{\text{mixed}}}{\partial \pi_i(b_i^F, b_j^F)} < 0\right)$.

In what follows, we use mixed-strategy profit as the outside option for firms that consider signing contracts. The rationale for firms is thus to sign contracts to increase and lock in profit as compared to mixed-strategy profit that includes the probability of miscoordination. To address the multiplicity of outcomes for $\pi_i(b_i^F, b_j^F)$, we simulate Equation (15) with $\pi_i(b_i^F, b_j^F) = 0$ and when assuming the highest miscoordination profits, that is for $\pi_i(b_i^F, b_j^F)$ close to $\pi_i(b_i^V, b_j^F)$.[13]

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[12]Results hold when running the same simulations with differentiated price caps for Astoria and Keyspan instead.

[13]Equation (5) of the model section characterizes that the maximum permissible free-riding profits for firm i, by design of the equilibrium, are bound by $\pi_i(b_i^V, b_j^F) = \pi_i(b_i^F, b_j^F) + \varepsilon$, with ε close to zero. Otherwise, for $\pi_i(b_i^V, b_j^F) \leq \pi_i(b_i^F, b_j^F)$, the volunteer's dilemma vanishes.

4.2.2 | Monte Carlo simulations

We first calculate the model deterministically, given the ex-post observed parameters for the year 2006. Note that these parameters may not have been in line with the data the firms were calculating their strategies with. To address this, we in addition pursue a Monte Carlo approach, where we take the perspective that while firms are completely informed about the true underlying parameters, the researcher is not. We thus simulate the model for different parameters the firms could assume. Specifically, we vary the parameter of the model on, first, demand, and, second, fringe capacities. We perform these two different simulations to increase the robustness of our results.[14]

For simplicity, we simulate the model for different draws from a normal distribution. For both fringe capacity and demand, the mean of the normal distribution is the observed 2006 value. We then assume a standard deviation of about one typically sized large power plant in the sample (500 MW).[15] This standard deviation accounts for additional investment or divestment by fringe firms, or alternatively, for lower or higher demand for capacity as announced by the regulator. We then draw 2,000 times from this distribution, once for demand and simulate a stylized contract year, and a second time using 2000 draws for the fringe capacity to again simulate a stylized contract year.

4.2.3 | Predictions

Given our theoretical analysis and the above computation of counterfactual profit, we investigate the following predictions:

Prediction 1. *Astoria and Keyspan face a volunteer's dilemma in the absence of the contract. More specifically,*

$$b_j^* = \min\{\arg \max_{b_j}(a - db_j - k_i - k_f)b_j, \bar{p}\} = \bar{p} \quad \forall j = 1, 2 \quad \text{and} \quad i \neq j,$$

which we calculate once deterministically for the observed 2006 values, once for 2000 draws for the demand parameter a, and once for 2000 draws from the distribution for k_f.[16]

Prediction 2. *The contract quantity agreed on by Astoria and Keyspan corresponds to the sufficient contract quantity defined in Corollary 2,*

$$-s_i \approx D(\bar{p}) - k_j - k_f \approx 1,800.$$

The right-hand side represents the observed contract quantity of 1,800 MW. We apply the same 2000 draws of demand and fringe capacity, respectively, as before.

Prediction 3. *Firms have an incentive to sign the contract if the two following conditions hold*

$$\pi_i\left(b_i^F, b_j^V\right) - (\bar{p} - 7.07)1800 \geq \pi_i^{\text{mixed}}$$

$$\pi_j\left(b_j^V, b_i^F\right) + (\bar{p} - 7.57)1800 \geq \pi_j^{\text{mixed}}.$$

Note that profits of the inframarginal firm i with the contract are independent of draws from demand and fringe capacity. This is because profits for firm i with the contract are known with certainty, as firm i just sells its own capacity at a known price $\bar{p}$. In contrast, π_i^{mixed}, π_j^{mixed}, and $\pi_j(b_j^V, b_i^F)$ depend on the draw from demand and fringe capacities.

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[14]We thank one reviewer for suggesting that draws from demand and fringe capacity are known to firms but unknown to the researcher. In this setting, the empirical approach takes account of our model with complete information.

[15]As documented in the NYISO yearly reports during our observations period, typical capacity additions of new gas-fired plants were about 500–600 MW.

[16]In our first simulation for different draws from demand parameter a, we hold k_i, k_j, and the fringe capacities fixed, and simulate the model for different draws for demand where the means are $a = 10,381$ MW and $a = 10,421$ MW for summer and winter, respectively. Following Table 1, for our second simulation, the mean of the distribution k_f takes the 2006 summer value of 5,034 MW or, when we simulate winter auctions, 5,486 MW. On this second simulation, all other parameters for demand and data on k_i, k_j then take the deterministic values for the year 2006.

4.3 | Results

Below, we first report our results for the deterministic computation and for the simulation with different demand parameters. We subsequently present our findings when simulating different draws from the distribution of fringe capacities.

4.3.1 | Existence of a volunteer's dilemma

To show that the volunteer's dilemma exists, it suffices to show that the price cap is binding for both firms (see Corollary 1). We simulate the optimal bidding function in Equation (4) for both firms. We indeed find that, conditional on volunteering, both firms' optimal strategy was to offer the price cap. More specifically, in line with Prediction 1, we find that the price cap is binding for both firms. Given these results, we conclude that the two large firms face a volunteer's dilemma in the absence of a contract. This finding holds when calculating the model deterministically and when simulating the model with repeated draws for demand. Figure 1 illustrates the model runs for the different demand parameters and shows that the simulated optimal bids are clearly above the price cap ($p < .05$).

4.3.2 | Sufficient contracting

Second, we investigate whether the contract implements credible commitment for Astoria to always free-ride. This is the case if the contract rules out coordination failure where both firms free-ride. We have shown that this equilibrium is ruled out for all values of $\pi_i(b_i^F, b_j^F)$ if the contract quantity agreed on by the firms is at least equal to the sufficient contract quantity defined in Corollary 2.

Calculating the model once deterministically for the observed 2006 data, we find a sufficient contract quantity of 1,814 MW, which is remarkably close to the observed contract volume of 1,800 MW. When running our simulations using different demand realizations, we find a mean of the sufficient contract quantity of 1,806 MW. We reject that this theoretical contract quantity of 1,806 MW is statistically different from the quantity specified in the contract of 1,800 MW ($p = 0.42$). In sum, the model runs show that the observed contract of 1,800 MW is remarkably close and
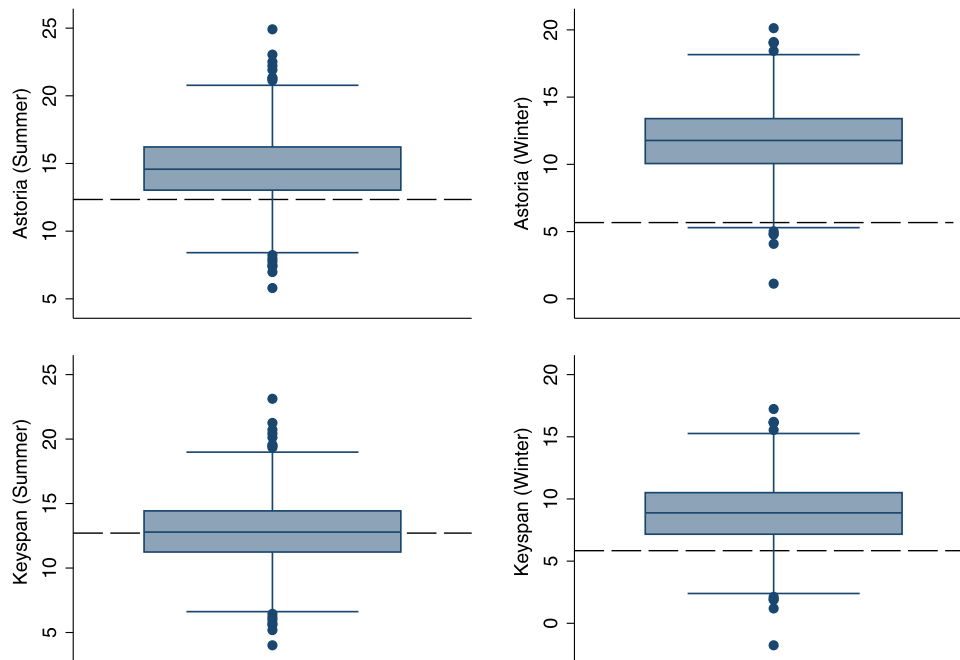
FIGURE 1 Optimal unconstrained clearing bids (box plot) and price cap (dashed line). The two upper box plots display the optimal clearing prices of Astoria against 2000 demand draws using parameters from Summer 2006 (left) and Winter 2006 (right). The two box plots below refer to the corresponding optimal clearing bids of Keyspan [Color figure can be viewed at wileyonlinelibrary.com]
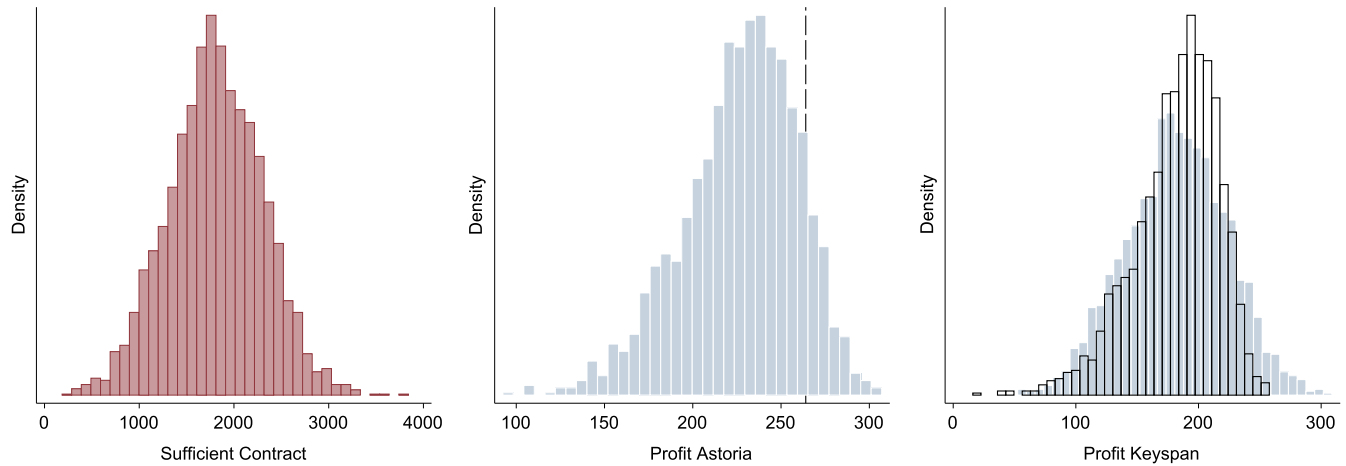
FIGURE 2 The left panel shows the density of simulated optimal contract volumes as in Corollary 2 from 2000 demand draws. The mean is equal to 1,806 MW, while the observed contract volume is 1,800 MW. The center and right panel show simulated profits for Astoria and Keyspan, respectively, for $\pi_i(b_i^F, b_j^F) = 0$. The solid distribution represents mixed-strategy profit. The transparent distribution represents profits with the contract for Keyspan. For Astoria, profits with the contract are deterministic and represented by the dashed vertical line. Profits are in million USD [Color figure can be viewed at wileyonlinelibrary.com]

large enough to ensure commitment for Astoria to free-ride in the pricing game. These findings support Prediction 2. The left panel of Figure 2 depicts the density of all simulation outcomes for the sufficient contract.

4.3.3 | Profitability

The contracts must be profitable for each firm. Therefore, we test whether profits with contracting are larger than simulated (mixed-strategy) profits without contracting. When simulating the model once deterministically, we find that it is almost always profitable for both firms to sign the contract. For Astoria, the contract is clearly payoff dominant. Calculated profits with the contract are about 15% larger than counterfactual mixed-strategy profits when simulating the largest mixed-strategy profits, that is, for $\pi_i(b_i^F, b_j^F) = 0$. When instead comparing the profits with the contract to counterfactual mixed-strategy profits with $\pi_i(b_i^F, b_j^F)$ close to $\pi_i(b_i^V, b_j^F)$, profits with the contract are about 36% larger. The profit dominance of the contract also becomes apparent in our simulations using different demand realizations, as shown in Figure 2. Astoria's profit with the contract are statistically higher than without it ($p < .01$).

For Keyspan, when calculating the model deterministically, the mixed-strategy profits are slightly larger than the profits with the contract for $\pi_i(b_i^F, b_j^F) = 0$ (about 3%), but clearly superior when calculating the model for $\pi_i(b_i^F, b_j^F)$ close to $\pi_i(b_i^V, b_j^F)$, where profits with the contract are about 20% larger than counterfactual profit. When simulating the model with different demand realizations and for the highest counterfactual profit with $\pi_i(b_i^F, b_j^F) = 0$, the contract statistically yields the same mean profit than mixed-strategy profit. Figure 2 presents the simulated profits for different demand draws. We reject that contract and counterfactual profits are different ($p = .90$) and therefore conclude that the contract is at least weakly payoff dominant for Keyspan. Overall, Prediction 3 holds over the range of different model simulations.[17]

4.3.4 | Results for different fringe capacities

Our findings remain valid when simulating the model with different draws from fringe capacity instead.[18] First, the price cap remains binding for both firms when simulating the model with different draws of fringe capacity around the

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[17]FERC (2008) reports realized net revenue for Keyspan in 2006 of 170 million USD. Our simulated average profit for Keyspan in 2006 is about 180 million USD. Thus the overall profit levels from our simulation compare relatively well.

[18]Note that apart from the different draws for the simulation, the mechanisms behind changes in fringe capacity and demand are similar. Moreover, we performed simulations using different demand slopes, albeit the slope did not change drastically during our observation period. Varying the slope parameter by about 5% yields results that closely resemble the deterministic model computation.

observed 2006 value. Hence, the volunteering dilemma exists. Figure B2 depicts the corresponding distribution of optimal volunteering bids for the different draws of fringe capacity.

Second, the simulated mean of the sufficient contract quantity as in Corollary 2 is 1,821 MW. While this value is statistically above 1,800 MW, the model runs are still remarkably close to the observed contract. We conclude that the contract is large enough to ensure commitment for Astoria to free-ride in the pricing game. The corresponding figure for different fringe capacities is shown in Figure B3.

Lastly, also the profit dominance of the contracts is confirmed. For Astoria, the profit dominance becomes clearly apparent in our simulations, as shown in the center panel of Figure B3. For Keyspan, we as before reject that contract and counterfactual profits are different ($p = .18$). These results stem from computations using the highest possible outside option that assumes $\pi_i(b_i^F, b_j^F) = 0$. Thus we conclude that the contract is at least weakly payoff dominant for Keyspan. Given these reassuring results for both dominant firms, we confirm Prediction 3.

5 | DISCUSSION

Last, we discuss our results and potential extensions to our contracting framework. We first consider the case of a unilateral contract where only one firm signs the contract derived in Lemma 2. In our empirical application, firms have avoided the volunteer's dilemma by signing two offsetting contracts of sufficient volumes. However, it is easy to show that the volunteer's dilemma also vanishes if only firm i signs a contract with the financial intermediary. As long as Lemma 2 holds and firm j is aware of the contract, firm i can credibly commit to always bid low. In this case, equilibria where firm i volunteers do not exist, and firm j instead volunteers and bids the price cap. As a result, firm i loses money via the contract but its overall profits are positive given the equilibrium response of firm j to bid at the price cap. Also, the financial intermediary that agrees to sign this contract benefits as, anticipating equilibrium play, it receives contract payments. Hence unilateral contracting suffices.[19]

Second, we consider the case of nonbinding price caps, as opposed to the case of binding price caps that we have considered in our empirical analysis. It is easy to show that firms can sign a contract that increases both firms' profits. If firms have similar offsetting forward positions as considered above, it is straightforward that contracting increases the market price if the cap is nonbinding. The volunteering bidder j signs a contract that guarantees transfer payments for higher prices than the strike price and is consequently willing to offer a higher bid, as $\frac{\partial b_j^V}{\partial s_j} > 0$. Crucially, the volunteering firm obtains the higher price not only for its sold units, but also for the quantity specified in the contract. Moreover, the increased spot profit due to the higher market price for the inframarginal firm is large enough to more than offset the contract payments it has to make to the pivotal bidder j. As in the case with binding price caps, there also exists a critical contract quantity that solves the volunteer's dilemma. We provide a more formal proof of this result in Appendix A.4. Yet, note that for the case of nonbinding price caps, it is clearly beneficial that the contract party with the net-buying position is the volunteering firm. For the case of binding price caps, one contract solves the coordination problem in that one firm commits to free-ride, independent of the counterparty. If price caps are nonbinding, a firm can use a similar strategy to commit to free-ride. However, the volunteering firm becomes the optimal counterparty, as only then contracts can establish both coordination and a higher clearing price.

Third, our theoretical case with nonbinding price caps is related to a competitive setup with differentiated products and forward markets as studied by Mahenc and Salanié (2004). The similarity to pricing strategies in differentiated product markets arises as the clearing price set by firm j uniformly applies to its rival firms. Our profit function in (2) is similar to the profit function in differentiated product markets, which typically can be represented by $\pi(b_i, b_j) = q(b_i, b_j) b_i$. In a differentiated product market each firm earns its own price, with price choices being strategic complements. In a uniform price auction, a higher clearing price set by one's rival directly translates into one's own higher profits. In this context, the rival's bids have a perfect complementarity with profits of inframarginal firms. Note that Einav and Nevo (2009) have already stressed the similarities between first-order conditions in differentiated product markets and auctions.

Last, we stress that coordination could also be achieved in a dynamic setup. Indeed, there is a literature on the effect of forward markets on repeated spot market competition (Ferreira, 2003; Green & Le Coq, 2010; Liski & Montero, 2006).

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[19]In line with this observation, FERC (2008) mentions that the low-bidding firm Astoria was the first to search for counterparties for their contracting offer. Keyspan only later agreed to become the counterparty via signing the offsetting contract with the same financial intermediary.

In a repeated setting, contracts can facilitate collusion, because they reduce the size of the spot market, cutting both the immediate gain from defection and the punishment for deviation. However, for collusion to occur all firms need to charge higher, collusive prices, while in uniform price auctions only one firm is needed to implement a noncompetitive clearing price. As such, even if dynamic considerations would result in one firm repeatedly being the volunteer, discounted profits across volunteering and free-riding firms will be extremely asymmetric. In contrast, the contracts studied here allow firms to support noncompetitive prices and redistribute profits toward the volunteer.

6 | CONCLUSION

This paper studies the use of forward contracts to coordinate on pricing strategies in product markets. Based on our empirical motivation, we model the product market as a multi-unit uniform price auction. We first characterize the volunteer's dilemma that firms are likely to face in multi-unit uniform price auctions with tight capacity constraints.

When only one firm (the "volunteer") is needed to increase the market clearing price, the firm setting the noncompetitive price does not sell the entire capacity while the others do. Thus, it is individually more profitable if one of the other rival firms is the price-setter. Conversely, taking the role of price-setter is a best response if no rival does. Hence there is a multiplicity of Nash equilibria that differ substantially in individual firms' profit.

When firms face such a volunteer's dilemma, coordination failure can occur when no firm lifts the price above competitive levels. However, we show that with appropriate contract agreements, firms can solve this dilemma. We also provide a quantitative assessment of our theoretical predictions by using data from procurement auctions for power-generating capacity. We show that contracts, as signed by the two dominant firms in the case we study, can act as a coordination device to ensure and maintain a noncompetitive market price.

The benefits of derivative markets, such as reduced price exposure, increased market liquidity, and enhanced information transmission, are well known. Nonetheless, we show that derivatives can facilitate anticompetitive behavior in a subtle way without affecting observed market prices. The possibility of using financial contracts as a coordination device should be considered by regulators when assessing market efficiency. Also, auctioneers selling or procuring items in multi-unit uniform price auctions have to consider the possibility that side payments increase bidder profits.

DATA AVAILABILITY STATEMENT

All data are available on the website of the New York independent electricity system operator (NYISO). The data that support the findings of this study are available at https://www.nyiso.com.

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APPENDIX A: PROOFS

A.1 Sufficient symmetry

The volunteer's dilemma exists if it is costly to volunteer but still a best response when the competing firm does not. It therefore suffices to show that volunteering profits are lower than nonvolunteering profits, but higher than profits when no firm volunteers. We start by deriving the first condition, that is, when volunteering profits are lower than free-riding profits.

Assume first that the price cap is nonbinding. If firm j volunteers, it earns profit equal to $\frac{(a - k_f - k_i)^2}{4d}$. If, now, firm i volunteers, and firm j does not, profits for firm j would yield $\frac{a - k_f - k_j}{2d} k_j$. Volunteering profits are hence lower than nonvolunteering profits for all

$$k_j < \hat{k}_j(k_i) = \frac{1}{2}(a - k_f + \sqrt{4(a - k_f)k_i - (a - k_f)^2 - 2k_i^2}),$$

which follows from equating volunteering and nonvolunteering profits and solving for the critical k_j.

Assume now that the price cap is binding for firm j but not for firm i. Everything is the same but the profits when firm j volunteers (and firm i does not) become $\bar{p}(D(\bar{p}) - k_f - k_i)$. The above inequality can be rewritten as follows:

$$k_j < \hat{k}_j(k_i) = \frac{1}{2}(a - k_f + \sqrt{(a - k_f)^2 + 8d(k_f + k_i - D(\bar{p}))\bar{p}}).$$

Note that if the price cap is binding for firm i with $k_i < k_j$, it must also be binding for firm j. Hence we ignore the case where the price cap is only binding for firm i. If the price cap is binding for both firms, the volunteer's dilemma always exists.

Finally, for the second condition, that profits in each case need to be lower than profits when no firm volunteers, consider the case where both firms free-ride and set maximum bids $b_i^F = \bar{b}_i$. By construction of $\bar{b}_i$ as defined in Equation (5), it must always be beneficial for one firm to deviate and volunteer.

A.2 Critical contract positions with $\pi_I(b_I^F, b_j^F) = 0$

Below, we provide another argument that the contract with $\pi_i(b_i^F, b_j^F) = 0$ is the largest contract and implements commitment also for all $\pi_i(b_i^F, b_j^F) > 0$. We start by recalling the critical contract quantity in Equation (11):

$$s_i < -\frac{\pi_i(b_i^V, b_j^F) - \pi_i(b_i^F, b_j^F)}{\bar{p} - p^*}.$$

Any s_i satisfying the above condition must be negative and hence the inframarginal firm is a net seller. Furthermore, the following argument shows that the sufficient contract with $b_i^F = b_j^F = 0$ of $s_i^* = -D(\bar{p}) + k_f + k_j = -\frac{\pi_i(b_i^V, b_j^F)}{\bar{p}}$ induces commitment also at any positive miscoordination price $p^* < \bar{p}$. Next, note that for any positive miscoordination price $p^* < \bar{p}$, firm i's sales are at least $D(\bar{p}) - k_f - k_j$. First, it will only sell more because for any $p^* < \bar{p}$ we have $D(p^*) > D(\bar{p})$. Second, firm i may sell its entire capacity k_i at the miscoordination price p^*. Using these lowest miscoordination sales of $D(\bar{p}) - k_f - k_j$, we conclude that miscoordination profit must at least be $(D(\bar{p}) - k_f - k_j)p^*$. Applying this lower bound for miscoordination profit to Equation (11), the critical contract can be reduced to $s_i^* < -\frac{\pi_i(b_i^V, b_j^F) - \pi_i(b_i^F, b_j^F)}{\bar{p} - p^*} < -D(\bar{p}) + k_f + k_j$, which equals exactly the critical contract with $b_i^F = b_j^F = 0$. Now, if firm i indeed sells more and $\pi_i(b_i^F, b_j^F) > (D(\bar{p}) - k_f - k_j)p^*$, the nominator of $-\frac{\pi_i(b_i^V, b_j^F) - \pi_i(b_i^F, b_j^F)}{\bar{p} - p^*}$ must decrease, and with it the critical short position. Thus the critical contract quantity with $\pi_i(b_i^F, b_j^F) = 0$ suffices for committing to free-ride for any $\pi_i(b_i^F, b_j^F) \geq 0$.

A.3 Mixed-strategy profits

Resolving Equation (14) with $\pi_i(b_i^F, b_j^F) = 0$ yields the following optimal mixed strategy, that is, probability of volunteering:

$$\rho_j = \frac{\pi_i\left(b_i^V, b_j^F\right)}{\pi_i\left(b_i^V, b_j^F\right) + \pi_i\left(b_i^F, b_j^V\right) - \pi_i\left(b_i^V, b_j^V\right)}.$$

We can then write firm i's mixed-strategy profits as follows:

$$\rho_i\left(\rho_j\pi_i\left(b_i^V, b_j^V\right) + (1 - \rho_j)\pi_i\left(b_i^V, b_j^F\right)\right) + (1 - \rho_i)\rho_j\pi_i\left(b_i^F, b_j^V\right) = \frac{\pi_i\left(b_i^V, b_j^F\right)\pi_i\left(b_i^F, b_j^V\right)}{\pi_i\left(b_i^V, b_j^F\right) + \pi_i\left(b_i^F, b_j^V\right) - \pi_i\left(b_i^V, b_j^V\right)}.$$

$$= \rho_j\pi_i\left(b_i^F, b_j^V\right)$$

With positive free-riding bids $b_i^F > 0 \quad \forall\, i = 1, 2$, the mixed-strategy of firm j derives from

$$\rho_j\pi_i\left(b_i^V, b_j^V\right) + (1 - \rho_j)\pi_i\left(b_i^V, b_j^F\right) = \rho_j\pi_i\left(b_i^F, b_j^V\right) + (1 - \rho_j)\pi_i\left(b_i^F, b_j^F\right),$$

where the left- (right-)hand side represents profits when firm i volunteers (free-rides). Solving for firm j's probability to volunteer yields

$$\rho_j = \frac{\pi_i\left(b_i^V, b_j^F\right) - \pi_i\left(b_i^F, b_j^F\right)}{\pi_i\left(b_i^V, b_j^F\right) - \pi_i\left(b_i^F, b_j^F\right) + \pi_i\left(b_i^F, b_j^V\right) - \pi_i\left(b_i^V, b_j^V\right)}.$$

Equilibrium mixed-strategy profit of firm i then becomes

$$\rho_i\left(\rho_j\pi_i\left(b_i^V, b_j^V\right) + (1 - \rho_j)\pi_i\left(b_i^V, b_j^F\right)\right) + (1 - \rho_i)\left(\rho_j\pi_i\left(b_i^F, b_j^V\right) + (1 - \rho_j)\pi_i\left(b_i^F, b_j^F\right)\right)$$

$$= \frac{\pi_i\left(b_i^V, b_j^V\right)\pi_i\left(b_i^F, b_j^F\right) - \pi_i\left(b_i^V, b_j^F\right)\pi_i\left(b_i^F, b_j^V\right)}{\pi_i\left(b_i^F, b_j^F\right) - \pi_i\left(b_i^V, b_j^F\right) - \pi_i\left(b_i^F, b_j^V\right) + \pi_i\left(b_i^V, b_j^V\right)}.$$

The first derivative of this last expression with respect to $\pi_i(b_i^F, b_j^F)$ is strictly negative. This implies that mixed-strategy profits with $\pi_i(b_i^F, b_j^F) = 0$ constitute an upper bound.

A.4 Nonbinding price caps

Consider the case where the price cap is nonbinding before contracting. Contracts in this case increase producer rent by increasing the clearing price: The price-setting firm j increases the clearing price to some $b_j^V (s_j > 0) > b_j^V (s_j = 0)$. The inframarginal firm i writes a contract with $-s_j = s_i < 0$. When the forward price is set such that $b_j^V (s_j > 0) > p^s$, firm i transfers rents to firm j as compensation for reducing its sales. In contrast, firm i earns additional rents on its full inframarginal capacity (without reduced sales). Hence the contract transfers parts of these additional rents to firm j. Note that in this case the condition for a sufficiently large contract changes. Specifically, the condition that leads to Corollary 2. in the main text changes to

$$\frac{(k_f + k_j - a)^2 - s_i^2}{4d} + s_i\left(\frac{(a - k_f - k_j) + s_i}{2d} - p^s\right) < -p^s s_i.$$

Rearranging yields

$$s_i < -a + k_f + k_j$$

as the sufficient contract quantity that guarantees equilibria where firm *j* volunteers. Note that in both cases with and without binding price caps, the optimal contract for any free-riding firm implies that it sells forward its residual demand (residual demand at the price cap for binding price caps and residual demand at a price of zero when price caps do not bind).
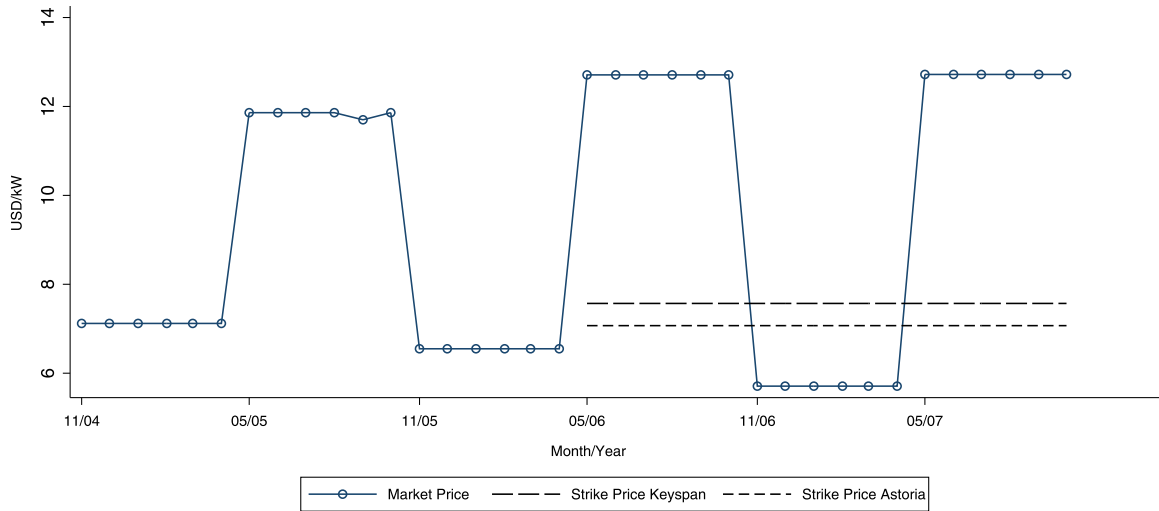
APPENDIX B

FIGURE B1 Market prices and strike prices three seasons before and after contract start date. The respective strike prices are in dashed lines and signal the start date of the contract in May 2006
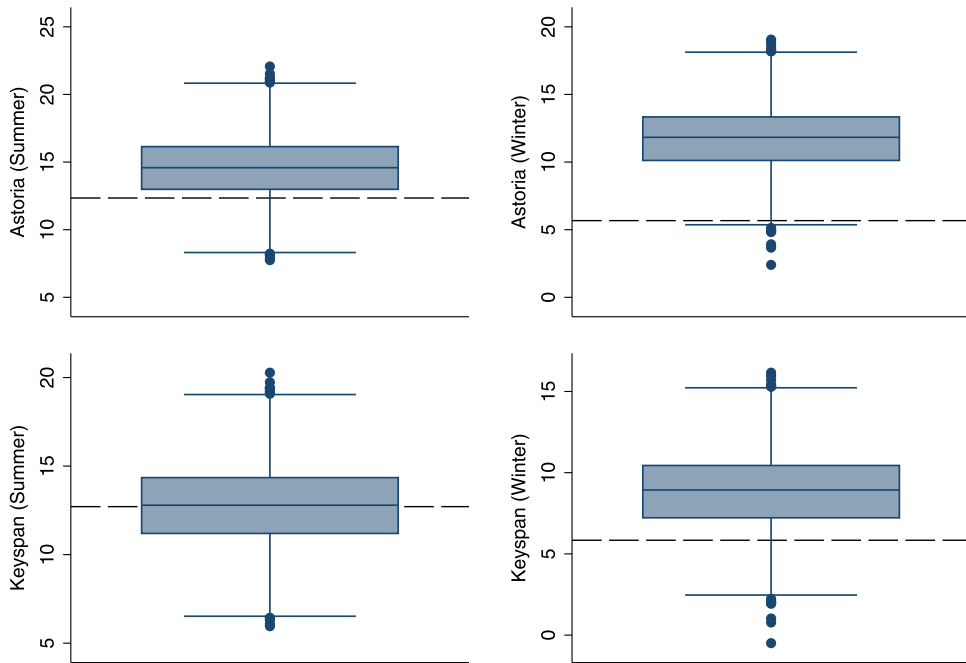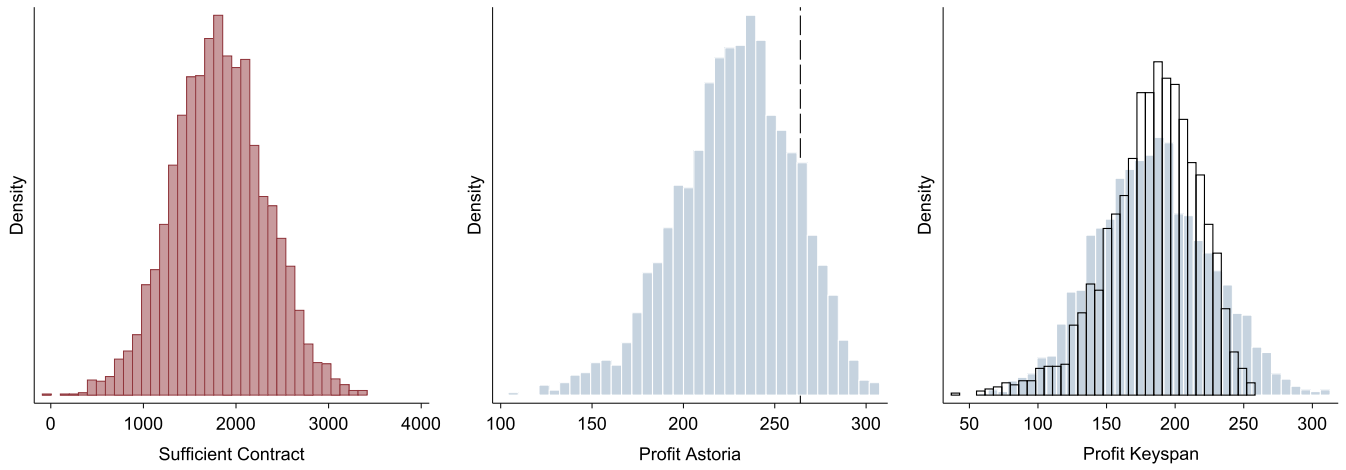

FIGURE B2 Optimal unconstrained clearing bids (box plot) and price cap (dashed line). The two upper box plots display the optimal clearing prices of Astoria against 2000 fringe draws using parameters from Summer 2006 (left) and Winter 2006 (right). The two box plots below refer to the corresponding optimal clearing bids of Keyspan

FIGURE B3 The left panel shows the density of simulated optimal contract volumes as in Corollary 2. from 2000 fringe draws. The mean is equal to 1,821 MW, while the observed contract volume is 1,800 MW. The center and right panel show simulated profits for Astoria and Keyspan, respectively, for $\pi_i(b_i^F, b_j^F) = 0$. The solid distribution represents mixed-strategy profit. The transparent distribution represents profits with the contract for Keyspan. For Astoria, profits with the contract are deterministic and represented by the solid vertical line. Profits are in million USD

FIGURE B4 The Figure depicts the step-wise nature of supply bids in the New York City capacity market. It shows supply bids and demand for May 2006. Demand is in black, all supply bids in blue. All capacity sold ahead of the spot auction (about 6,850 MW) is added at a bid of zero. The clearing bid is equal to the price cap of 12.71 USD. All capacity submitted at this price belongs to one firm ID